

THREE-GROUP ZOOM LENS INCLUDING AT LEAST ONE ASPHERIC LENS SURFACE

BACKGROUND OF THE INVENTION

Three-group zoom lenses that include, in order from the object side, a first lens group of negative refractive power, a second lens group of positive refractive power, and a third lens group for use in cameras are known in the prior art. These three-group zoom lenses have become
5 widely used because they are compact and provide favorable correction of aberrations.

Recently, digital cameras and video cameras have rapidly become popular, and these cameras are advantageously small and capable of providing high image quality with small aberrations, including distortion, characteristics similarly desired for previous types of cameras. On the other hand, conditions related to the use of solid state image pickup elements, such as
10 CCD's, must be satisfied that do not pertain to the previous types of cameras.

Auto-focus is almost essential in digital cameras and video cameras and faster focusing is desired in such cameras. Therefore, inner focusing or rear focusing that reduces the weight of the moving lens elements, assures the moving lens elements are close to the camera body, and allows easy driving of the lens elements is frequently used as the focusing mode in zoom lenses for such
15 cameras. For example, Japanese Laid-Open Patent Application 2000-284177 discloses a rear focusing zoom lens for achieving rapid focusing and that provides high resolution images having improved aberration correction.

The desired high image quality and small size of digital cameras and video cameras has led to reducing the pixel size (i.e., area per pixel) of the CCD of the image pickup element. As
20 the pixel size is decreased, greater correction of spherical aberration is demanded in order to achieve the higher resolution required of the zoom lens by reducing the pixel size. However, while the zoom lens described in the above-mentioned Japanese application provides favorable correction of distortion and curvature of field, it is difficult to simultaneously reduce the spherical aberration the desired amount. If plural aspheric lenses are used in the first lens group,
25 which is one approach to solving the problem, distortion, curvature of field and spherical aberration can be simultaneously favorably corrected, but the zoom lens tends to become too

large and too expensive to manufacture.

BRIEF SUMMARY OF THE INVENTION

The present invention relates to a three-group zoom lens that can simultaneously favorably correct distortion, curvature of field, and spherical aberration and provides high resolution while being compact and relatively inexpensive to manufacture. More specifically, the present invention relates to a three-group zoom lens that includes at least one aspheric lens element, is suitable for use in a digital camera or video camera having a solid state image pickup element, and has a zoom ratio of about 3 while maintaining a short overall length of the optical system and providing favorable correction of aberrations.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more fully understood from the detailed description given below and the accompanying drawings, which are given by way of illustration only and thus are not limitative of the present invention, wherein:

Fig. 1 shows cross-sectional views of the zoom lens according to Embodiment 1 at the wide-angle end W and the telephoto end T;

Fig. 2 shows cross-sectional views of the zoom lens according to Embodiment 3 at the wide-angle end W and the telephoto end T;

Figs. 3A - 3D show aberrations of the zoom lens according to Embodiment 1 at the wide-angle end;

Figs. 3E - 3H show aberrations of the zoom lens according to Embodiment 1 at an intermediate position;

Figs. 3I - 3L show aberrations of the zoom lens according to Embodiment 1 at the telephoto end;

Figs. 4A - 4D show aberrations of the zoom lens according to Embodiment 2 at the wide-angle end;

Figs. 4E - 4H show aberrations of the zoom lens according to Embodiment 2 at an

intermediate position;

Figs. 4I - 4L show aberrations of the zoom lens according to Embodiment 2 at the telephoto end;

Figs. 5A - 5D show aberrations of the zoom lens according to Embodiment 3 at the wide-angle end;

Figs. 5E - 5H show aberrations of the zoom lens according to Embodiment 3 at an intermediate position; and

Figs. 5I - 5L show aberrations of the zoom lens according to Embodiment 3 at the telephoto end.

DETAILED DESCRIPTION

A general description of the three-group zoom lens of the present invention that pertains to all three embodiments of the invention will first be described with reference to Fig. 1 that shows Embodiment 1. In Fig. 1, lens elements are referenced by the letter L with a subscript denoting their order from the object side of the zoom lens along the optical axis X, from L_1 to L_6 . Similarly, radii of curvature of the surfaces of various optical elements, including the lens surfaces, are referenced by the letter R with a subscript denoting their order from the object side of the zoom lens, from R_1 to R_{14} . The on-axis surface spacings along the optical axis X of various optical surfaces are referenced by the letter D with a subscript denoting their order from the object side of the zoom lens, from D_1 to D_{13} . In the same manner, the three lens groups are labeled G1 through G3 in order from the object side of the zoom lens.

The term “lens group” is defined in terms of “lens elements” and “lens components” as explained herein. The term “lens element” is herein defined as a single transparent mass of refractive material having two opposed refracting surfaces that are positioned at least generally transversely of the optical axis of the zoom lens. The term “lens component” is herein defined as (a) a single lens element spaced so far from any adjacent lens element that the spacing cannot be neglected in computing the optical image forming properties of the lens elements or (b) two or more lens elements that have their adjacent lens surfaces either in full overall contact or so close

together that the spacings between adjacent lens surfaces of the different lens elements are so small that the spacings can be neglected in computing the optical image forming properties of the two or more lens elements. Thus, some lens elements may also be lens components. Therefore, the terms "lens element" and "lens component" should not be taken as mutually exclusive terms.

5 In fact, the terms may frequently be used to describe a single lens element in accordance with part (a) above of the definition of a "lens component." The term "lens group" is used herein to define an assembly of one or more lens components that are fixed or are movable as a single unit relative to other lens groups.

10 As shown in Fig. 1, a diaphragm stop 3 that controls the amount of light that passes through the zoom lens is included as part of the second lens group G2. An image pickup device, such as a CCD (not shown), is arranged at the image plane 1. Additionally, a low-pass filter or an infrared blocking filter 2 is arranged between the third lens group G3 and the image plane 1.

15 As shown in Fig. 1, the zoom lens of the present invention includes, in order from the object side, a first lens group G1 of negative refractive power, a second lens group G2 of positive refractive power, and a third lens group G3 of positive or negative refractive power. The first lens group G1 and the second lens group G2 are moved relative to one another during zooming from the wide-angle end to the telephoto end so as to reduce the distance between the two lens groups G1 and G2. The first lens group G1 includes at least one aspheric lens surface.

20 Additionally, all the aspheric lens surfaces of the zoom lens satisfy the following equation:

$$Z = [(Y^2/R) / \{1 + (1 - K \cdot Y^2/R^2)^{1/2}\}] + \sum A_i |Y|^i \quad \dots \text{(Equation A)}$$

where

Z is the length (in mm) of a line drawn from a point on the aspheric surface at a distance Y from the optical axis to the tangential plane of the aspheric surface vertex,
 R is the radius of curvature (in mm) of the aspheric surface on the optical axis,
 Y is the distance (in mm) from the optical axis,
 K is the eccentricity of the aspheric lens surface, and
 A_i is the ith aspheric coefficient and the summation extends over i equals one to twenty.

It has been known to prescribe the shape of aspheric lens surfaces using the above Equation (A) with the aspheric coefficients A_4 , A_6 , A_8 , A_{10} and A_{12} being non-zero (see, for example, Patent No. US 6,661,584 B2). If, in attempting to improve lens performance, the number of non-zero aspheric coefficients was increased by including non-zero coefficients for, for example A_{14} , A_{16} , etc., the optical design software and lens processing programming has conventionally been considered to be too complicated to be practical using available computers.

In contrast, the zoom lens of the present invention may prescribe the shape of an aspheric surface not only in conventional terms of aspheric coefficients with low even numbered subscripts being non-zero in Equation (A) above, but also in terms of aspheric coefficients with low odd numbered subscripts being non-zero in accordance with the recent demand for higher resolution optical systems and improvements in computer performance. By using aspheric coefficients with both even and odd subscripts being non-zero in Equation (A) above, both even and odd powers of Y help determine the shape of the aspheric lens surface. In particular, at least one lens element of the first lens group G1 may include an aspheric lens surface according to Equation (A) using aspheric coefficients having both even and odd subscripts that are non-zero so that both even and odd powers of Y help determine the shape of the at least one aspheric lens surface. The shape of the central lens surface area including the optical axis and the shape of an area outside this central area (hereinafter called the peripheral area) of the aspheric lens surface can be independently determined to some extent by increasing the parameters of Equation (A) that determine the aspheric shape to include non-zero aspheric coefficients with odd numbered subscripts.

Generally in a three-group zoom lens having an aspheric lens surface in the first lens group G1, the aspheric lens surface is designed to favorably correct the curvature of field and distortion because the peripheral areas extend far from the central area in this lens group. Thus, the shape of the central area that primarily affects the spherical aberration can be independently determined to some extent while maintaining the shape of the peripheral area for improving such curvature of field and distortion. Thus, spherical aberration, distortion and curvature of field can be simultaneously favorably corrected.

As the number of terms used in Equation (A) increases, the optical performance generally improves. However, using more terms increases the difficulty of designing and manufacturing the lens systems, thereby increasing costs, which must be balanced against any improvement in optical performance. For example, an acceptable correction of aberrations may be obtained by adding parameters that contribute to the determination of the shape of the central area even if only one term of the odd numbered power three of Y is added to the terms of the even numbered powers four, six, eight, and ten, generally used previously. As another example, when Equation (A) is provided with aspheric coefficients A_4 through A_{10} that are non-zero, the shape of the central area may appropriately correct spherical aberration based on the lower power terms, and the shape of the peripheral area may appropriately correct curvature of field and distortion based on the higher power terms.

Alternatively or additionally, in the zoom lens of the present invention with the lens group arrangement as described above, including the first lens group G1 with an aspheric lens, Equation (A) may prescribe an aspheric lens surface in terms of aspheric coefficients with subscripts smaller than sixteen that are non-zero and aspheric coefficients with subscripts of sixteen or larger that are non-zero so that powers of Y of sixteen or larger help determine the shape of an aspheric lens surface.

Thus, two techniques are disclosed for defining the aspheric shape of a lens surface according to Equation (A) above, each technique being usable separately or in conjunction with the other technique: (1) using aspheric coefficients with both even and odd subscripts that are non-zero so that both even and odd powers of Y help determine the shape of the aspheric lens surface according to Equation (A) above, and (2) using aspheric coefficients with subscripts of sixteen or larger that are non-zero so that powers of Y of sixteen or larger help determine the shape of the aspheric lens surface according to Equation (A) above.

In the first case, the parameters determining the shape of an aspheric surface are increased by using terms in Equation (A) above with aspheric coefficients having low odd-numbered subscripts that are non-zero that add to the terms with aspheric coefficients having low even-numbered subscripts that are non-zero. In the second case, the parameters are increased by using

terms with aspheric coefficients having subscripts of sixteen or larger that are non-zero, along with terms with aspheric coefficients having subscripts smaller than sixteen that are non-zero as known previously. In both cases, similar corrections of aberrations can be achieved, and the shape of the central area including the optical axis and the shape of the peripheral area of the aspheric lens surface can be independently determined to some extent so that the shape of the central area can be determined for correcting spherical aberration based on the lower power terms. Simultaneously, the shape of the peripheral area can be determined for correcting curvature of field and distortion based on the higher power terms. Thus, spherical aberration, distortion and curvature of field can be simultaneously favorably corrected in a similar manner in both cases.

Furthermore, the two techniques may be used together. That is, using Equation (A) above, terms with aspheric coefficients having low odd-numbered subscripts that are non-zero and with aspheric coefficients having subscripts of sixteen or larger that are non-zero may both be added to conventional applications of Equation (A).

Embodiments 1 - 3 of the present inventions will now be individually described with further reference to the drawings. In the following descriptions, references will be frequently made to a "lens element." However, as set forth above, it is understood that numerous of the lens elements described below are also lens components and may be replaced by lens components that include more than one lens element. Additionally, although Embodiments 1 - 3 that follow are specifically disclosed using a particular one of the techniques of (a) using aspheric coefficients having both even and odd subscripts that are non-zero so that both even and odd powers of Y help determine the shape of the at least one aspheric lens surface according to Equation (A) above, or (b) using aspheric coefficients having subscripts of sixteen or larger that are non-zero so that powers of Y of sixteen or larger help determine the shape of the at least one aspheric lens surface according to Equation (A) above, any of Embodiments 1 - 3 described below could easily be modified to use the other technique or to use both techniques in order to improve the imaging.

Embodiment 1

In Embodiment 1, as shown in Fig. 1, the three-group zoom lens includes, in order from the object side, a first lens group G1 of negative refractive power, a second lens group G2 of positive refractive power, and a third lens group G3 of positive refractive power. The first lens group G1 and the second lens group G2 are moved relative to one another during zooming from the wide-angle end to the telephoto end so as to reduce the distance between the two lens groups, and the second lens group G2 and the third lens group G3 are moved relative to one another during zooming from the wide-angle end to the telephoto end so as to increase the distance between these two lens groups. Additionally, the third lens group G3 is moved toward the object side during focusing from a focus at infinity to a near point focus. In this manner, the three-group zoom lens of Embodiment 1 provides changes in focal length by moving the three lens groups along the optical axis X while maintaining high light transmission to a focused image at the imaging plane 1.

The first lens group G1 includes, in order from the object side, a first lens element L_1 of negative refractive power and a meniscus shape with its concave lens surface on the image side and a second lens element L_2 of positive refractive power and a meniscus shape with its convex lens surface on the object side. Both lens surfaces of the first lens element L_1 are aspheric, and the aspheric shapes are prescribed by Equation (A) above with aspheric coefficients with both even and odd numbered subscripts being non-zero. Thus, both even and odd powers of Y help determine the shape of the aspheric lens surfaces of the first lens element L_1 .

The second lens group G2 includes, in order from the object side, a diaphragm stop 3, a lens component formed of a third lens element L_3 having a biconvex lens shape with the same curvature on both lens element surfaces, and a fourth lens element L_4 having a biconcave shape with its lens surface of greater curvature on the object side and that is intimately bonded to the third lens element L_3 , and a fifth lens element L_5 of positive refractive power and a meniscus shape with its convex lens surface on the object side. The term “intimately bonded” is defined herein generally to mean that adjacent refractive surfaces of two lens elements have substantially the same curvature and are held in direct fixed contact or are separated by a thin layer of

transparent adhesive (too thin to be considered in optical computations) that fixes the lenses together, the latter being commonly referred to as a “cemented” lens element arrangement.

Both lens surfaces of the fifth lens element L_5 are aspheric, and the aspheric shapes are prescribed by Equation (A) above, but only aspheric coefficients with even numbered subscripts are non-zero. Thus, in Embodiment 1, only even powers of Y help determine the shape of the aspheric lens surfaces of the fifth lens element L_5 .

The third lens group $G3$ is formed of a sixth lens element L_6 having a biconvex shape with both lens surfaces having the same curvature.

By using lens elements of prescribed shapes and including aspheric lens elements L_1 and L_5 as described above, the three-group zoom lens of Embodiment 1 achieves high resolution with good aberration correction while maintaining a compact six lens element construction.

Preferably, the first aspheric lens element on the object side is not only in lens group $G1$ but is also positioned as far from the diaphragm stop 3 as possible. Specifically, in Embodiment 1 this is done by choosing lens element L_1 as an aspheric lens element with two aspheric lens surfaces designed according to the technique described above of using aspheric coefficients with both even and odd subscripts being non-zero so that both even and odd powers of Y help determine the shape of the aspheric lens surfaces according to Equation (A) above. Because the peripheral areas of the lens elements extend far from the central area in this lens group, substantial simultaneous correction of spherical aberration, distortion and curvature of field is possible.

Preferably, the three-group zoom lens satisfies the following conditions:

$$d / fw < 0.15 \quad \dots \text{Condition (1)}$$

$$vL_3 - vL_4 > 15 \quad \dots \text{Condition (2)}$$

where

d is the on-axis spacing between the image-side lens surface of the biconcave lens element in the second lens group and the lens element having positive refractive power and a meniscus shape in the second lens group;

fw is the focal length of the three-group zoom lens at the wide-angle end;

vL_3 is the Abbe number of the biconvex lens element of the second lens group, and
 vL_4 is the Abbe number of the biconcave lens element of the second lens group.

Satisfying Condition (1) helps reduce the overall thickness of the second lens group G2. Thus, by choosing lens element L_1 as an aspheric lens element with two aspheric lens surfaces designed according to the technique described above of using aspheric coefficients with both even and odd subscripts that are non-zero so that both even and odd powers of Y help determine the shape of the aspheric lens surfaces according to Equation (A) above, the zoom lens can be made compact. Satisfying Condition (2) helps correct lateral color at the wide-angle end and axial chromatic aberration at the telephoto end.

When Condition (1) is satisfied, it is preferable, as shown in Fig. 1, that an image-side edge portion of the fourth lens element L_4 and an object-side edge portion of the fifth lens element L_5 in the second lens group G2 include flat surfaces that contact each other. This reduces the labor and time for adjusting and aligning the lenses of the second lens group G2, including the fifth lens L_5 which is an aspheric lens, and improves assembly accuracy, such as that related to eccentric positioning of lens elements, that may cause deterioration of image quality and prevent high resolution imaging. Alternatively, high resolution imaging is similarly obtained when each of an image-side edge portion of the fourth lens element L_4 and an object-side edge portion of the fifth lens element L_5 includes a flat surface, and the flat surfaces are parallel and in contact with one of two opposite parallel sides of a plate, thus sandwiching the plate between the flat surfaces of the lens elements.

Because in the three-group zoom lens of Embodiment 1 the third lens group G3 is fixed at a predetermined reference position corresponding to a particular focus position, for example - infinity, when the zoom lens is retracted, the focusing operation is easily achieved by an actuator, such as a motor, and the retracted length of the zoom lens may be made very short. Additionally, by using intimately bonded lens elements in the second lens group G2, the second lens group G2 is made thinner, which also contributes to a shorter overall length of the three-group zoom lens of Embodiment 1 in the retracted position.

Table 1 below lists the surface number #, in order from the object side, the radius of curvature R (in mm) of each surface near the optical axis, the on-axis surface spacing D (in mm) between surfaces, as well as the refractive index N_d and the Abbe number v_d (both at the d-line of 587.6 nm) of each lens element for Embodiment 1. Listed in the bottom portion of Table 1 are the focal length f and the f-number F_{NO} at the wide-angle and telephoto ends, and the maximum field angle 2ω at the wide-angle end and the telephoto end for Embodiment 1.

TABLE 1

#	R	D	N_d	v_d
1*	289.1745	1.00	1.80348	40.4
2*	5.6490	2.16		
3	8.1430	1.83	1.92286	20.9
4	13.5774	D_4 (variable)		
5	∞ (stop)	0.40		
6	5.5720	3.54	1.71300	53.9 (vL_3)
7	-5.5720	0.56	1.66680	33.1 (vL_4)
8	7.1924	0.15		
9*	5.7845	1.05	1.56865	58.6
10*	7.6893	D_{10} (variable)		
11	24.9237	1.81	1.48749	70.2
12	-24.9237	4.05		
13	∞	0.91	1.51680	64.2
14	∞			

$$f = 5.8 - 15.96 \text{ mm} \quad F_{NO} = 2.9 - 5.0 \quad 2\omega = 62.3^\circ - 23.7^\circ$$

The lens surfaces with a * to the right of the surface number in Table 1 are aspheric lens surfaces, and the aspheric surface shape of these lens elements is expressed by Equation (A) above.

Table 2 below lists the values of the constants K and $A_3 - A_{10}$ used in Equation (A) above for each of the aspheric lens surfaces (#1 and #2) of lens element L_1 of Table 1. Table 3 below lists the values of the constants K, A_4 , A_6 , A_8 , and A_{10} used in Equation (A) above for each of the aspheric lens surfaces (#9 and #10) of lens element L_5 of Table 1. Aspheric coefficients that are not present in Tables 2 and 3 are zero. An "E" in the data indicates that the number following the "E" is the exponent to the base 10. For example, "1.0E-2" represents the number 1.0×10^{-2} .

TABLE 2

	Aspheric Factor	#1	#2
5	K	-1.6541660	-0.2646114
	A ₃	-1.7066764E-4	-3.6236190E-4
	A ₄	2.0859084E-3	3.2772158E-3
	A ₅	-5.2991230E-4	-7.3500188E-4
	A ₆	-2.8005201E-5	1.7210526E-5
	A ₇	3.2753797E-5	2.4496153E-5
10	A ₈	-4.7044463E-6	-5.6434100E-7
	A ₉	1.2466006E-7	-6.9394753E-7
	A ₁₀	1.1261201E-8	6.0890837E-8

TABLE 3

	#	K	A ₄	A ₆	A ₈	A ₁₀
15	9	-3.9999935	3.3683977E-3	-1.9741958E-4	-1.4767677E-5	-1.6776015E-7
	10	0.1092475	3.6796439E-3	3.3159871E-5	-1.8135579E-5	-1.4023255E-7

In the zoom lens of Embodiment 1, lens groups G1 and G2 move to vary their separations and the separation of lens group G2 from lens group G3 also changes during zooming.

Therefore, the values of the on-axis spacings D₄ and D₁₀ vary. Table 4 below lists the values of the variables D₄ and D₁₀ (i.e., the on-axis spacings) at the wide-angle end (Wide), at an intermediate position, and at the telephoto end (Tele). The focal length of the zoom lens when focused at is 5.80 mm at the wide-angle end, 9.63 mm at an intermediate position, and 15.96 mm at the telephoto end.

TABLE 4

	#	Wide	Intermediate	Tele
25	D ₄	14.56	7.24	2.84
	D ₁₀	5.28	9.40	16.19

The zoom lens of Embodiment 1 of the present invention satisfies both Conditions (1) and (2) above as set forth in Table 5 below.

TABLE 5

Condition No.	Condition	Value
(1)	$d / f_w < 0.15$	0.026
(2)	$vL_3 - vL_4 > 15$	20.8

Figs. 3A - 3D show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 1 at the wide-angle end. Figs. 3E - 3H show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 1 at an intermediate position, and Figs. 3I - 3L show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 1 at the telephoto end. In Figs. 3A, 3E, and 3I, the spherical aberration is shown for the wavelengths 587.6 nm (the d-line), 460.0 nm, and 615.0 nm. In the remaining figures, ω is the half-field angle. In Figs. 3B, 3F and 3J, the astigmatism is shown for the sagittal image surface S and the tangential image surface T. In Figs. 3C, 3G and 3K, distortion is measured at 587.6 nm (the d-line). In Figs. 3D, 3H and 3L, the lateral color is shown for the wavelengths 460.0 nm and 615.0 nm relative to 587.6 nm (the d-line). As is apparent from these figures, the various aberrations are favorably corrected over the entire range of zoom.

Embodiment 2

Embodiment 2 is very similar to Embodiment 1 and therefore only the differences between Embodiment 2 and Embodiment 1 will be explained. A main difference from Embodiment 1 is that the shape of some of the aspheric surfaces are prescribed by the above Equation (A) in terms of aspheric coefficients with even numbered subscripts of sixteen or larger being non-zero as well as aspheric coefficients with even numbered subscripts smaller than sixteen being non-zero. Thus, even-numbered powers of Y of sixteen or larger, as well as even-numbered powers of Y smaller than sixteen, help determine the shape of some of the aspheric lens surfaces. In other words, in Embodiment 2, both lens surfaces of the first lens element L_1 are prescribed by the above Equation (A) in terms of aspheric coefficients, with the even-numbered coefficients having subscripts of sixteen or larger being non-zero, as well as the even-numbered coefficients having subscripts smaller than sixteen being non-zero.

Additionally, in Embodiment 2, the sixth lens element L_6 that forms the third lens group G3 has a biconvex lens shape with its lens surface of greater curvature on the object side.

By using aspheric lens surfaces defined using Equation (A) in the first lens element

L_1 and the fifth lens element L_5 as described above, the three-group zoom lens of Embodiment 2 achieves high resolution and favorable aberration correction while maintaining a compact six lens element arrangement, including a short extension of the zoom lens in a retracted position in a camera body.

Embodiment 2 also differs from Embodiment 1 in its lens element configuration by different radii of curvature of lens surfaces, different eccentricities and aspheric coefficients of the aspheric lens surfaces, and some different optical element surface spacings.

Table 6 below lists the surface number #, in order from the object side, the radius of curvature R (in mm) of each surface near the optical axis, the on-axis surface spacing D (in mm) between surfaces, as well as the refractive index N_d and the Abbe number v_d (both at the d-line of 587.6 nm) of each lens element for Embodiment 2. Listed in the bottom portion of Table 6 are the focal length f and the f-number F_{NO} at the wide-angle and telephoto ends, and the maximum field angle 2ω at the wide-angle end and the telephoto end for Embodiment 2.

TABLE 6

#	R	D	N_d	v_d
1*	407.8429	1.00	1.80348	40.4
2*	5.7054	2.19		
3	8.2507	1.81	1.92286	20.9
4	13.8073	D_4 (variable)		
5	∞ (stop)	0.40		
6	5.4784	3.57	1.71300	53.9 (v_{L_3})
7	-5.4784	0.56	1.66680	33.1 (v_{L_4})
8	7.1924	0.15		
9*	6.0289	1.05	1.50869	56.0
10*	8.1296	D_{10} (variable)		
11	19.8035	1.77	1.48749	70.2
12	-34.6993	3.92		
13	∞	0.91	1.51680	64.2
14	∞			

$$f = 5.81 - 15.98 \text{ mm} \quad F_{NO} = 2.9 - 5.0 \quad 2\omega = 62.3^\circ - 23.7^\circ$$

The lens surfaces with a * to the right of the surface number in Table 6 are aspheric lens surfaces, and the aspheric surface shape of these lens elements is expressed by Equation (A)

above.

Table 7 below lists the values of the constants K and A_4 , A_6 , A_8 , A_{10} , A_{12} , A_{14} , A_{16} , A_{18} , and A_{20} used in Equation (A) above for each of the aspheric lens surfaces (#1 and #2) of lens element L_1 of Table 6. Table 8 below lists the values of the constants K, A_4 , A_6 , A_8 , and A_{10} used in Equation (A) above for each of the aspheric lens surfaces (#9 and #10) of lens element L_5 of Table 6. Aspheric coefficients that are not present in Tables 7 and 8 are zero. An “E” in the data indicates that the number following the “E” is the exponent to the base 10. For example, “1.0E-2” represents the number 1.0×10^{-2} .

TABLE 7

Aspheric Factor	#1	#2
K	0	0
A_4	1.7110893E-3	2.5780279E-3
A_6	-2.0909876E-4	-3.1798526E-4
A_8	2.0190176E-5	4.6615960E-5
A_{10}	-1.3971824E-6	-5.2321154E-6
A_{12}	6.7534263E-8	4.3261277E-7
A_{14}	-2.2008009E-9	-2.4552167E-8
A_{16}	4.5660836E-11	8.9191847E-10
A_{18}	-5.4152607E-13	-1.8582400E-11
A_{20}	2.7882919E-15	1.6845886E-13

TABLE 8

#	K	A_4	A_6	A_8	A_{10}
9	-5.0453318	2.9793278E-3	-2.7004844E-4	-1.5257602E-5	-1.7165122E-7
10	0.0028545	3.3602408E-3	1.0036066E-5	-1.7692234E-5	-1.3898743E-7

In the zoom lens of Embodiment 2, lens groups G1 and G2 move to vary their separations and the separation of lens group G2 from lens group G3 also changes during zooming. Therefore, the values of the on-axis spacings D_4 and D_{10} vary. Table 9 below lists the values of the variables D_4 and D_{10} (i.e., the on-axis spacings) at the wide-angle end (Wide), at an intermediate position, and at the telephoto end (Tele). The focal length of the zoom lens when focused at infinity is 5.81 mm at the wide-angle end, 9.64 mm at an intermediate position, and 15.98 mm at the telephoto end.

TABLE 9

#	Wide	Intermediate	Tele
D ₄	14.59	7.24	2.83
D ₁₀	5.38	9.48	16.26

The zoom lens of Embodiment 2 of the present invention satisfies both Conditions (1) and (2) above as set forth in Table 10 below.

TABLE 10

Condition No.	Condition	Value
(1)	$d / f_w < 0.15$	0.026
(2)	$vL_3 - vL_4 > 15$	20.8

Figs. 4A - 4D show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 2 at the wide-angle end. Figs. 4E - 4H show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 2 at an intermediate position, and Figs. 4I - 4L show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 2 at the telephoto end. In Figs. 4A, 4E, and 4I, the spherical aberration is shown for the wavelengths 587.6 nm (the d-line), 460.0 nm, and 615.0 nm. In the remaining figures, ω is the half-field angle. In Figs. 4B, 4F and 4J, the astigmatism is shown for the sagittal image surface S and the tangential image surface T. In Figs. 4C, 4G and 4K, distortion is measured at 587.6 nm (the d-line). In Figs. 4D, 4H and 4L, the lateral color is shown for the wavelengths 460.0 nm and 615.0 nm relative to 587.6 nm (the d-line). As is apparent from these figures, the various aberrations are favorably corrected over the entire range of zoom.

Embodiment 3

Embodiment 3 is similar to Embodiment 1 and therefore only the differences between Embodiment 3 and Embodiment 1 will be explained. As shown in Fig. 2, the three-group zoom lens of Embodiment 3 includes, in order from the object side, a first lens group G1 having negative refractive power, a second lens group G2 having positive refractive power, and a third lens group G3 having negative refractive power. The first lens group G1 and the second lens

group G2 are moved during zooming from the wide-angle end to the telephoto end so as to reduce the distance between these two lens groups, and the second lens group G2 and the third lens group G3 are moved so as to maintain a constant distance between these two lens groups at the time of zooming from the wide-angle end to the telephoto end. Thus, the lens frames of lens groups G2 and G3 can be constructed on a unified frame, simplifying the design, construction, and operation of the three-group zoom lens. The third lens group G3 is separately moved to the object side at the time of focusing from infinity to the near point.

In this manner, the three-group zoom lens of Embodiment 3 provides changes in focal length by moving the three lens groups along the optical axis X while maintaining high light transmission to a focused image at the imaging plane 1.

The first lens group G1 includes, in order from the object side: a first lens element L_1 of negative refractive power and a biconcave shape having lens surfaces of different curvature, and with the lens surface of greater curvature on the image side; and, a second lens element L_2 having positive refractive power and a meniscus shape with its convex lens surface on the object side. Both lens surfaces of the first lens element L_1 are aspheric, and the aspheric shapes are prescribed by Equation (A) above with aspheric coefficients that are non-zero for both even-numbered and odd-numbered values of the subscript i . Thus, both even and odd powers of Y help determine the shape of the aspheric lens surfaces of the first lens element L_1 .

The second lens group G2 includes, in order from the object side, a diaphragm stop 3, a lens component formed of a third lens element L_3 having a biconvex lens shape with its lens surface of greater curvature on the object side, a combined lens component formed of a fourth lens element L_4 having a biconcave shape with surfaces of different curvature and its surface of greater curvature on the image side intimately bonded to a fifth lens element L_5 having a biconvex lens shape and surfaces of different curvature, with its surface of greater curvature on its object side.

The third lens group G3 is formed of a sixth lens element L_6 having negative refractive power and a meniscus lens shape with its concave surface on the object side.

Both lens surfaces of the third lens element L_3 are aspheric, and the aspheric shapes are

prescribed by Equation (A) above using only non-zero aspheric coefficients having even-numbered values of i . Thus, only even-numbered powers of Y help determine the shape of the aspheric lens surfaces of the third lens element L_3 .

Embodiment 3 also differs from Embodiment 1 in its lens element configuration by different radii of curvature of the lens surfaces, different eccentricities and aspheric coefficients of the aspheric lens surfaces, different optical element surface spacings, and some different refractive indexes and Abbe numbers of the materials of lens elements.

By using lens elements of prescribed shapes, including aspheric lens elements L_1 and L_3 as described above, the three-group zoom lens of Embodiment 3 achieves high resolution with favorable aberration correction while maintaining a compact, six lens element construction.

Table 11 below lists the surface number #, in order from the object side, the radius of curvature R (in mm) of each surface near the optical axis, the on-axis surface spacing D (in mm) between surfaces, as well as the refractive index N_d and the Abbe number v_d (both at the d-line of 587.6 nm) of each lens element for Embodiment 3. Listed in the bottom portion of Table 11 are the focal length f and the f-number F_{NO} at the wide-angle and telephoto ends, and the maximum field angle 2ω at the wide-angle end and the telephoto end for Embodiment 3.

TABLE 11

#	R	D	N_d	v_d
1*	-77.8625	1.20	1.50869	56.0
2*	4.6904	4.19		
3	9.3491	2.30	1.76182	26.5
4	13.1830	D_4 (variable)		
5	∞ (stop)	0.30		
6*	6.7143	2.95	1.50869	56.0
7*	-19.4875	1.25		
8	-187.9980	1.04	1.83400	37.2
9	4.9330	3.59	1.51633	64.1
10	-10.0411	3.47		
11	-12.3476	1.03	1.50869	56.0
12	-15.3094	D_{12} (variable)		
13	∞	1.75	1.51680	64.2
14	∞			
$f = 5.76 - 16.13 \text{ mm}$ $F_{NO} = 2.9 - 4.8$ $2\omega = 62.2^\circ - 23.2^\circ$				

The lens surfaces with a * to the right of the surface number in Table 11 are aspheric lens surfaces, and the aspheric surface shape of these lens elements is expressed by Equation (A) above.

Table 12 below lists the values of the constants K and $A_3 - A_{10}$ used in Equation (A) above for each of the aspheric lens surfaces (#1 and #2) of lens element L_1 of Table 11 and Table 13 below lists the values of the constants K, A_4 , A_6 , A_8 , and A_{10} used in Equation (A) above for each of the aspheric lens surfaces (#6 and #7) of lens element L_3 of Table 11. Aspheric coefficients that are not present in Tables 12 and 13 are zero. An "E" in the data indicates that the number following the "E" is the exponent to the base 10. For example, "1.0E-2" represents the number 1.0×10^{-2} .

TABLE 12

Aspheric Factor	#1	#2
K	24.07997	-0.31638
A_3	0.6964052E-3	0.6740893E-3
A_4	0.8066175E-4	0.9554210E-3
A_5	0.1501386E-5	-0.1501880E-4
A_6	-0.5010894E-5	0.5185462E-6
A_7	0.3349340E-6	0.1819851E-5
A_8	0.4924292E-7	-0.6694942E-6
A_9	-0.7307155E-8	0.1659582E-7
A_{10}	0.3668512E-9	0.8524903E-8

TABLE 13

#	K	A_4	A_6	A_8	A_{10}
6	0.376671	-0.6808610E-4	-0.5381899E-5	-0.4454396E-6	-0.1976232E-7
7	-26.0101	-0.2521280E-3	0.4946846E-5	-0.1619543E-5	0.2549204E-7

In the zoom lens of Embodiment 3, during zooming, lens groups G1 and G2 move to vary their separations and lens group G3 moves with lens group G2. Therefore, the values of the on-axis spacings D_4 and D_{12} vary. Table 14 below lists the values of the variables D_4 and D_{12} (i.e., the on-axis spacings) at the wide-angle end (Wide), at an intermediate position, and at the telephoto end (Tele). The focal length of the zoom lens when focused at infinity is 5.76 mm at the wide-angle end, 9.21 mm at an intermediate position, and 16.13 mm at the telephoto end.

TABLE 14

#	Wide	Intermediate	Tele
D_4	21.74	11.02	3.36
D_{12}	7.93	11.56	18.81

5 Figs. 5A - 5D show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 3 at the wide-angle end. Figs. 5E - 5H show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 3 at an intermediate position, and Figs. 5I - 5L show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 3 at the telephoto end. In Figs. 5A, 5E, and 5I, the spherical aberration is shown for the wavelengths 587.6 nm (the d-line), 460.0 nm, and 615.0 nm. In the remaining figures, ω is the half-field angle. In Figs. 5B, 5F and 5J, the astigmatism is shown for the sagittal image surface S and the tangential image surface T. In Figs. 5C, 5G and 5K, distortion is measured at 587.6 nm (the d-line). In Figs. 5D, 5H and 5L, the lateral color is shown for the wavelengths 460.0 nm and 615.0 nm relative to 587.6 nm (the d-line). As is apparent from these figures, the various aberrations are favorably corrected over the entire range of zoom.

The present invention is not limited to the aforementioned embodiments, as it will be obvious that various alternative implementations are possible. For example, the number of lens elements and lens components, values such as the radius of curvature R of each of the lens elements and components, the surface spacings D, the refractive index N_d , as well as the Abbe number v_d , are not limited to the examples indicated in each of the aforementioned embodiments, as other values can be adopted. Additionally, the number and the shapes of the lens elements and lens components may be varied. Furthermore, in applying Equation (A) above, other aspheric coefficients than those shown in Embodiments 1 - 3 may be non-zero so that other powers of Y than those described in Embodiments 1 - 3 may help determine the aspheric shape of one or more aspheric lens surfaces. Such variations are not to be regarded as a departure from the spirit and scope of the invention. Rather, the scope of the invention shall be defined as set forth in the following claims and their legal equivalents. All such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.